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Research Experience with a Plug-in Hybrid Electric Vehicle

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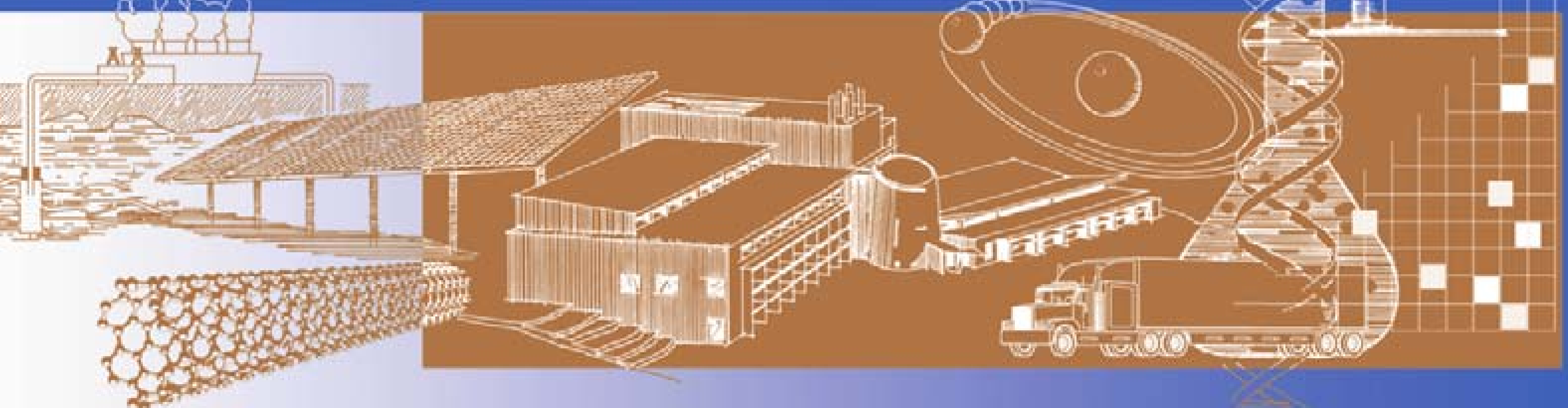

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Research Experience with a Plug-In Hybrid Electric Vehicle
EnergyCS Conversion of a Toyota Prius

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Abstract

The National Renewable Energy Laboratory (NREL) is using a Toyota Prius converted to be a plug-in hybrid electric vehicle (PHEV) to research the component impacts, system benefits, and technical barriers associated with PHEVs. The vehicle conversion was completed by EnergyCS and testing was conducted by NREL. Both pre- and post-conversion data has been collected and analyzed with a focus on changes in and the impact on the power electronics, energy storage, and vehicle system operation. The data includes both controlled dynamometer and on-road test results, particularly for hilly driving. Results highlight the petroleum savings benefits of PHEV technology. However, the thermal loads and usage patterns place additional design requirements on power electronics and energy storage systems. Results suggest that systems integration at a vehicle level is critical for maximizing the technology benefits. An increase in measured emissions was observed from the PHEV relative to the hybrid electric vehicle (HEV), however, the results are still below national standards. The test results will be used to explore advanced emissions control systems that take advantage of the availability of grid resources and the plug-in hybrid operating characteristics. In addition, the vehicle will be used to explore potential interaction between vehicles and renewable generation resources.

Keywords: Plug-in Hybrid Electric Vehicle, High Energy Battery, Thermal Systems, Power Electronics, Vehicle Systems, Testing.

1. Introduction

PHEV technology provides an opportunity for transitioning transportation energy demands from petroleum to electricity. Given the nearly 100% dependence on petroleum for transportation energy demands in the U.S., the transition to electricity brings diversity in the fuel source for future transportation energy needs. Simulation results have suggested significant petroleum displacement benefits from purpose-built plug-in hybrid electric vehicles [1, 2]. However, a vehicle with these capabilities is yet to be commercialized by a major manufacturer. In the meantime, there is much to be learned from a stock hybrid electric vehicle that has been converted to a plug-in hybrid electric vehicle.

The U.S. Department of Energy has developed a program plan to address the components and system barriers to commercialization and wide-spread use of PHEVs [3]. NREL supports this program through its Energy Storage, Advanced Power Electronics, and Vehicle System Analysis research activities. Thermal issues and design of energy storage and power electronics devices will have a significant impact on the vehicle system operation, performance, and cost.

This paper presents highlights of the exploratory research conducted at NREL on the current state of PHEV technology. The goals of the effort are to evaluate potential component thermal management challenges, impacts of environmental conditions, and the on-road performance characteristics of a 2006 Toyota Prius converted to be a PHEV by EnergyCS.

2. Approach

Using NREL's research investment funds, the Laboratory management purchased a 2006 Toyota Prius HEV to support PHEV research at NREL (Figure 1). In addition to the vehicle, 2 PHEV battery packs and installation services were acquired. A 9 kWh Li-Ion battery pack and energy management system from EnergyCS was installed in the vehicle, replacing the stock Prius battery pack. The EnergyCS PHEV conversion pack consists of Valence 1.2Ah Lithium-Iron Phosphate cells connected in series and parallel to provide a nominal system voltage of 235V. A 5 kWh Li-Ion supplemental PHEV pack from Hymotion was also purchased and will be installed in parallel with stock Prius battery pack at a future date. The project goal is to collect and analyze data from the vehicle that will improve the understanding of PHEV vehicle operation with a focus on systems thermal management and real-world conditions. The dynamometer testing was conducted at Environmental Testing Corporation (ETC), a commercial test facility certified to perform high altitude testing for vehicle OEMs. NREL's Energy Storage and Advanced Power Electronics teams collaborated with engineers at EnergyCS and ETC to perform this project.

Figure 1: NREL PHEV Test Bed (2006 Toyota Prius, 9kWh and 5kWh PHEV Battery Packs)

3. Instrumentation

The vehicle was instrumented for data collection beyond that available on the vehicle Control Area Network (CAN) bus. A CarDAQ+ CAN interface tool (Drew Technologies), notebook computer, and SnapMaster software (HEMData) were used to access and store CAN bus data. In addition, the data acquisition system is able to collect data on 6 analog channels. These have been used primarily for thermocouples installed throughout the vehicle. A GPS receiver (Garmin GPS18) is integrated with the data collection system to provide vehicle speed and elevation data for on-road evaluations. The vehicle also includes a custom interface and data logger referred to as a CDU developed by EnergyCS. The CDU monitors the status of the PHEV battery pack and CAN bus data to control how the vehicle uses the PHEV battery pack.

Data Collection Equipment

- CarDAQ+ from Drew Technologies
- TempDAQ from Drew Technologies
- SnapMaster software from HEMData
- Garmin GPS18 receiver
- Panasonic Toughbook
- K-type thermocouples
- Current sensor
- Semtech-DS

- Dynamometer at Environmental Testing Corp.
- CDU from EnergyCS

Temperature measurements

Using K-type thermocouples, the following measurement points have been instrumented. Given the limited number of analog channels currently available, only data of interest for the specific test being conducted are collected.

- Power Electronics (PE) Coolant – Radiator Outlet to PE Inlet
- PE Coolant – PE Outlet to Generator Inlet
- PE Coolant – Generator Outlet to Motor Inlet
- PE Coolant – Motor Inlet to Radiator Outlet
- Exhaust – Engine Outlet to Close-Coupled Catalyst Inlet
- Exhaust – Close-Coupled Catalyst Outlet to Underbody Catalyst Inlet
- Exhaust – Underbody Catalyst Outlet to Tailpipe
- Cabin – Breath temperature
- Cabin – Panel temperature
- Cabin – Battery inlet temperature
- Inverter case temperature
- Underhood air temperature
- Engine coolant temperature

The factory installed temperature sensors were also used for measuring and monitoring the battery pack and power electronic systems while data was collected through the CAN.

Other analog measurements

- PE Coolant - Pump voltage
- PE Coolant - Pump current

The current and voltage of the coolant pump in the power electronics coolant system was measured to provide the ability for correlation to fluid flowrate. A complete Prius power electronics coolant system is available for bench top experiments with similar instrumentation in the NREL Advanced Power Electronics Thermal Test Facility (Figure 2).

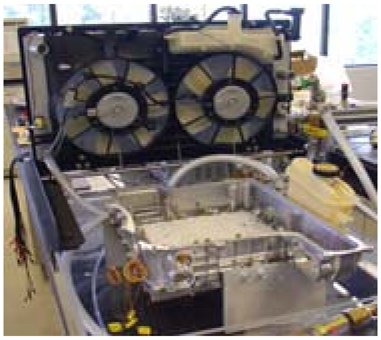


Figure 2: Toyota Prius Inverter and Cooling System for Bench Top Testing

Emissions sample probes

Sample probes using stainless steel tubing were installed in the vehicle's exhaust system for monitoring emissions at intermediate points (in addition to the tailpipe exhaust data typically collected during dynamometer testing). The following locations have been instrumented:

- Exhaust – Engine Outlet to Close-Coupled Catalyst Inlet
- Exhaust – Close-Coupled Catalyst Outlet to Underbody Catalyst Inlet
- Exhaust – Underbody Catalyst Outlet to Tailpipe

On-road emissions measurement
A unique feature of the on-road testing project is the use of a calibrated, portable system on-board the vehicle to measure vehicle emissions while driving on the road. A SEMTECH-DS portable emissions monitoring system (PEMs) was used for on-road emissions measurement. For use with the Prius, a 2.0" diameter exhaust flow meter was used, as shown in Figure 3. This is the smallest meter available from Sensors, Inc. Figure 4 is an image of the PEMs installed in the rear compartment of the vehicle.

Figure 3: PEMs Exhaust Flow Meter (2" diameter) attached to NREL PHEV

Figure 4: SEMTECH-DS installed in rear of NREL PHEV

4. Results

A stock 2006 Toyota Prius was acquired in November 2006. The vehicle was instrumented as detailed above for on-board data logging. Baseline testing of the stock vehicle was completed both on the road and on a dynamometer to provide data for comparison to the same vehicle after conversion to a PHEV. The vehicle was converted to a PHEV by EnergyCS in March 2007. Prior to installation, a Hybrid Pulse Power Characterization test [4] was completed on the battery pack. After several months of on-road testing, one of the 18 battery modules composing the PHEV battery pack was replaced as it was identified as faulty. Most of the data discussed in the paper was collected after the module replacement.

Testing of the NREL PHEV research vehicle is intended to supplement and compliment other sources of data on PHEV and hybrid component operation [5, 6]. The Denver, Colorado and the mountainous region near Denver provides and ideal location for evaluating the impacts of elevation changes on vehicle performance. Only a subset of the data collected to date will be presented in this paper. The following is a list of unique testing that has been completed where items in bold will be discussed in more detail.

1. Hybrid Pulse Power Characterization of EnergyCS pack prior to installation
2. Thermal imaging of EnergyCS battery module
3. SOC window testing of HEV
4. SOC catalyst temperature response test of HEV
5. **Comparison of HEV and PHEV on 'NREL to Eisenhower Tunnel' roundtrip**
6. PHEV and HEV urban driving on Colfax Ave. (urban-type driving)
7. Comparison of PHEV and HEV air conditioning system cool down testing
8. **Comparison of HEV and PHEV on NREL to Genesee roundtrip from both dynamometer and on-road testing**
9. PHEV over continuous on-road urban driving
10. PHEV over continuous on-road highway driving
11. **PHEV on-road emissions measurement with PEMs**
12. Dynamometer testing of HEV and PHEV under hot, cold, and mild ambient conditions
13. Steady-state PHEV component operation

Items not highlighted in bold in the above list will be the topics of future papers.

4.1 Comparison of HEV and PHEV on NREL to Eisenhower Tunnel roundtrip

NREL is located in Golden, Colorado on Interstate 70. Just to the west of NREL the highway climbs quickly, gaining ~1700 m of elevation over 50 miles, to the Eisenhower Tunnel. Due to the combination of highway speeds and rapid elevation changes this route presents a challenge for under-powered vehicles. The purpose of this test was to compare how the battery packs of the HEV and PHEV were used during a challenging mountain drive. Figure 5 and Figure 6, respectively, provide the overview of how the HEV and PHEV operated.

Differences in the battery pack current and voltage are clear. Current into the pack (charging) is shown as positive values. The HEV has more variation in both current and voltage. The PHEV operates at a nominally higher pack voltage. The state-of-charge (SOC) of the PHEV decreases, as expected, for nearly the entire first half of the trip while the HEV uses both regenerative braking events and the engine to recharge its battery when opportunistic to do so. Observed SOC ranged from 68.5% to 30% on the HEV and from 70.8% to 20.3% on the PHEV. The HEV consumed 2.04 gallons (7.7L) of fuel while the PHEV consumed 1.72 gallons (6.5L) of fuel. We expected to see the PHEV be able to recapture more regenerative braking energy than the HEV; however, both the PHEV and HEV charge currents were limited for different reasons. Based on the thermal data we suspect that the HEV charging was limited due to the high temperature (max observed = 56ºC) of the battery pack while the PHEV charging was limited due to several observed voltage excursions above 250 V. AvgT in Figures 4 and 5 is the average of the three battery temperatures reported on the CAN bus for the HEV and the average of the minimum and maximum reported module temperatures for the PHEV. The HEV pack had a higher initial temperature but both packs increased roughly 12-13ºC during the roundtrip.

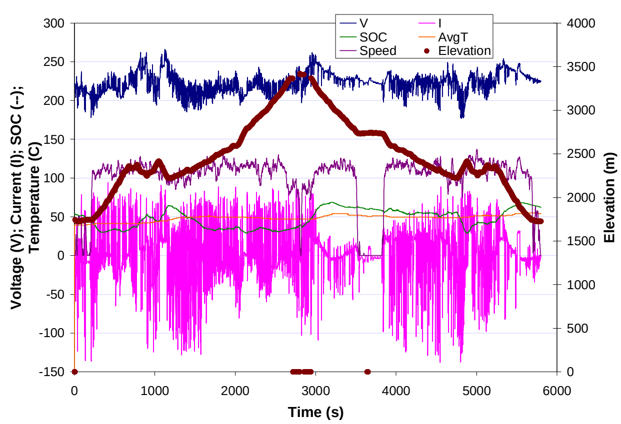


Figure 5: Stock Toyota Prius Operation on Eisenhower Tunnel Roundtrip

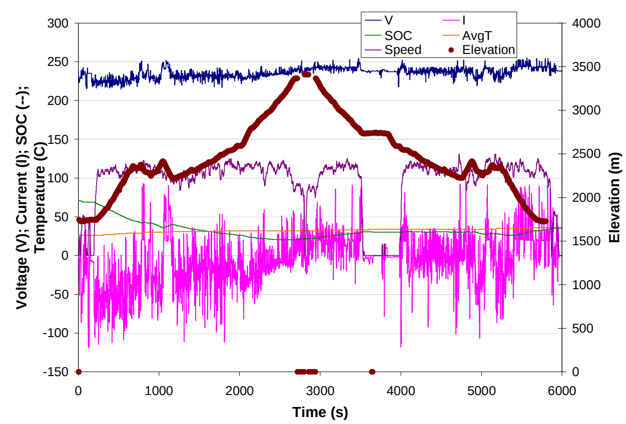


Figure 6: PHEV Toyota Prius Operation on Eisenhower Tunnel Roundtrip

Figure 7 is a scatter plot of the current and voltage data collected for both the HEV and PHEV during the NREL to Eisenhower Tunnel roundtrip. This shows the increase in nominal voltage from the HEV to the PHEV pack of ~15 V. The less steep slope of the PHEV fit also suggests that the internal resistance is slightly less than that of the stock NiMH HEV pack. Given the increase in capacity from 1.5kWh to 9kWh from the HEV to the PHEV, the same current represents a less severe relative loading and thus affects the slope and resistance comparison.

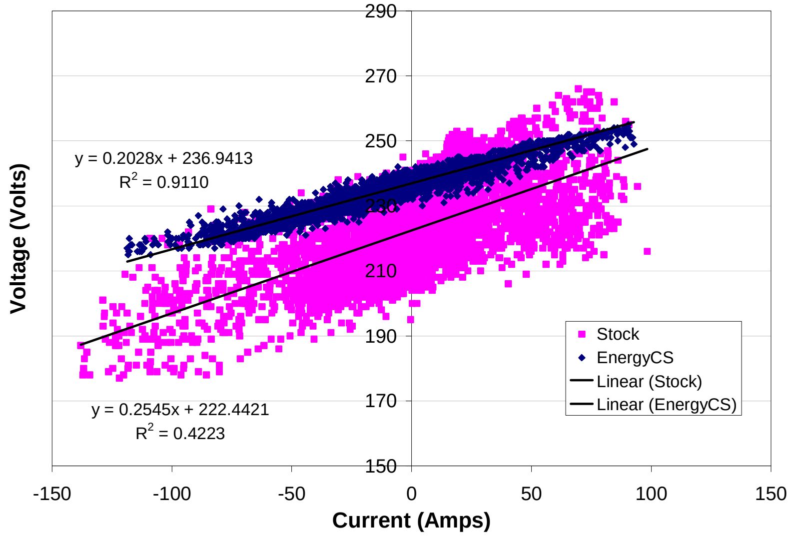


Figure 7: Comparison of Current and Voltage for Stock and PHEV during Eisenhower Tunnel Roundtrip

The roundtrip testing between NREL and Eisenhower tunnel suggests that this PHEV has the potential to capture additional regenerative braking energy if the overall system design is refined to avoid or allow high voltage events. Data suggests that thermal management of the NiMH pack in the Stock Prius can limit its performance while the less severe relative loading and the system thermal mass in a blended PHEV conversion is able to mitigate temperature excursions.

4.2 Comparison of HEV and PHEV on Genesee Roundtrip both On-road and Dynamometer

NREL, in collaboration with Environmental Testing Corporation, has developed a cycle and methodology for testing a vehicle over a cycle that includes changes in roadway grade both on the road and on the dynamometer. Drive cycle data was collected from the HEV prior to conversion. The data was processed and used as a custom drive cycle on the dynamometer with variable grade. Figure 8 shows the duty cycle including both speed and elevation changes. The HEV and PHEV have been driven both on the road and on the dynamometer over this cycle repeatedly. Although traffic and ambient conditions can influence the on-road results, comparison between data collected under both conditions provides valuable insights.

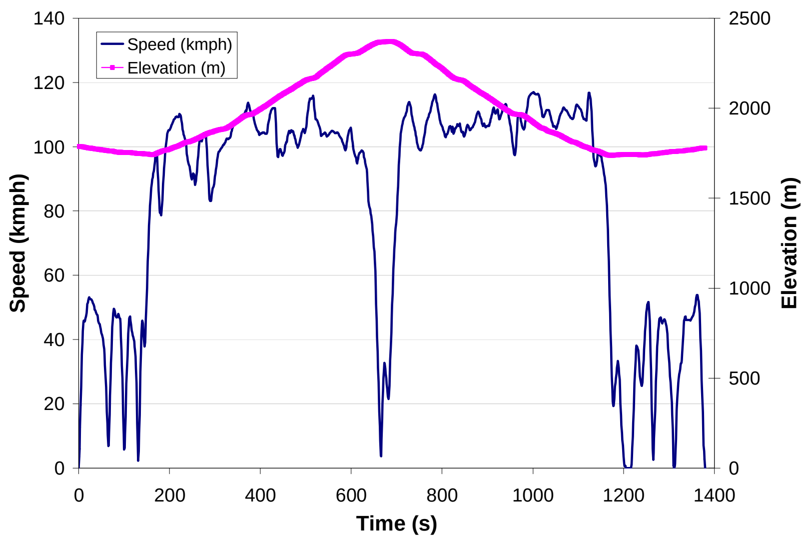


Figure 8: NREL to Genesee Roundtrip Duty Cycle for On-road and Dynamometer Testing

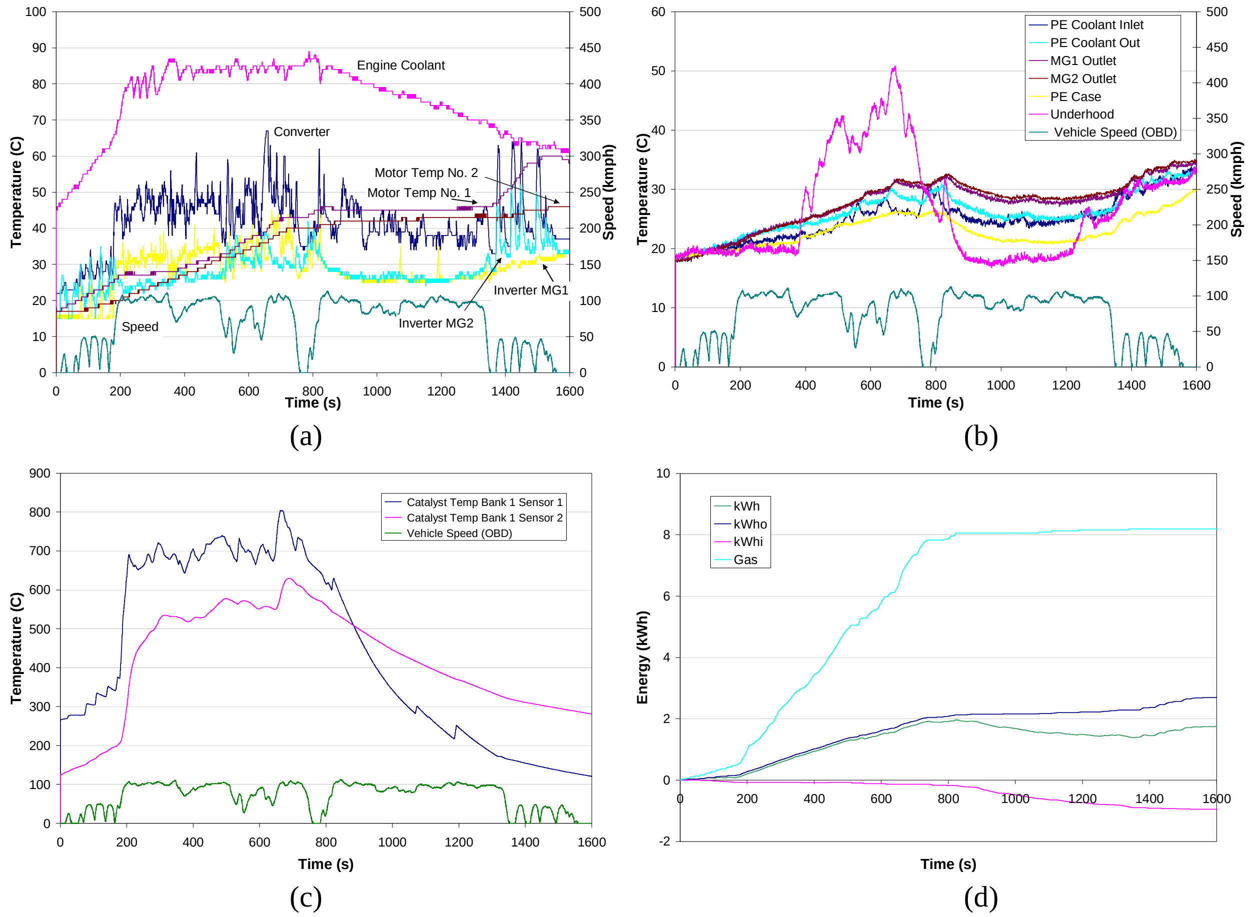


Figure 9: PHEV On-road NREL to Genesee Roundtrip Results

Figure 9a, provides a summary of information from the CAN bus regarding the thermal characteristics of the power electronics and electric drive system. "Converter" represents the temperature of the DC/DC converter, which observes the greatest thermal impacts during this cycle. The boost converter is used extensively at highway speeds for high speed motor operation. Motor usage is apparent from the rising Motor Temp No. 1 and No. 2 signals. Along with the CAN bus temperature signals, analog temperature data is collected for the power electronics coolant loop as shown in Figure 9b. Both the buffering capability of the coolant and the time lag between measurement locations make it more difficult to identify individual events. The combination of the moderate ambient temperature (~60^{o}F or 15^{o}C) and the thermal capacity of the system seem to suggest that it is able to accommodate the change in loading due to PHEV operation. However, other ambient conditions may have increased impact on the system performance. Figure 9c shows the response of the catalyst system to the duty cycle based on available CAN bus data. Both the PHEV and HEV (as will be shown later) have similar catalyst thermal trends for this cycle. Figure 9d, shows the cumulative energy flow within the vehicle. Gallons of gasoline are multiplied by 33.44 kWh/gal for comparison to electrical energy consumption. The battery energy values are integrals of power observed at the terminals (kWh = net, kWho = discharge, kWhi = charge) and thus do not include the efficiency of the battery. This test was started with an SOC of ~81%. The charge depleting nature of the PHEV biases toward discharging (kWho increasing while kWhi are stable). Gasoline consumption rises steadily during the climb and is nearly constant (engine off) for most of the descent.

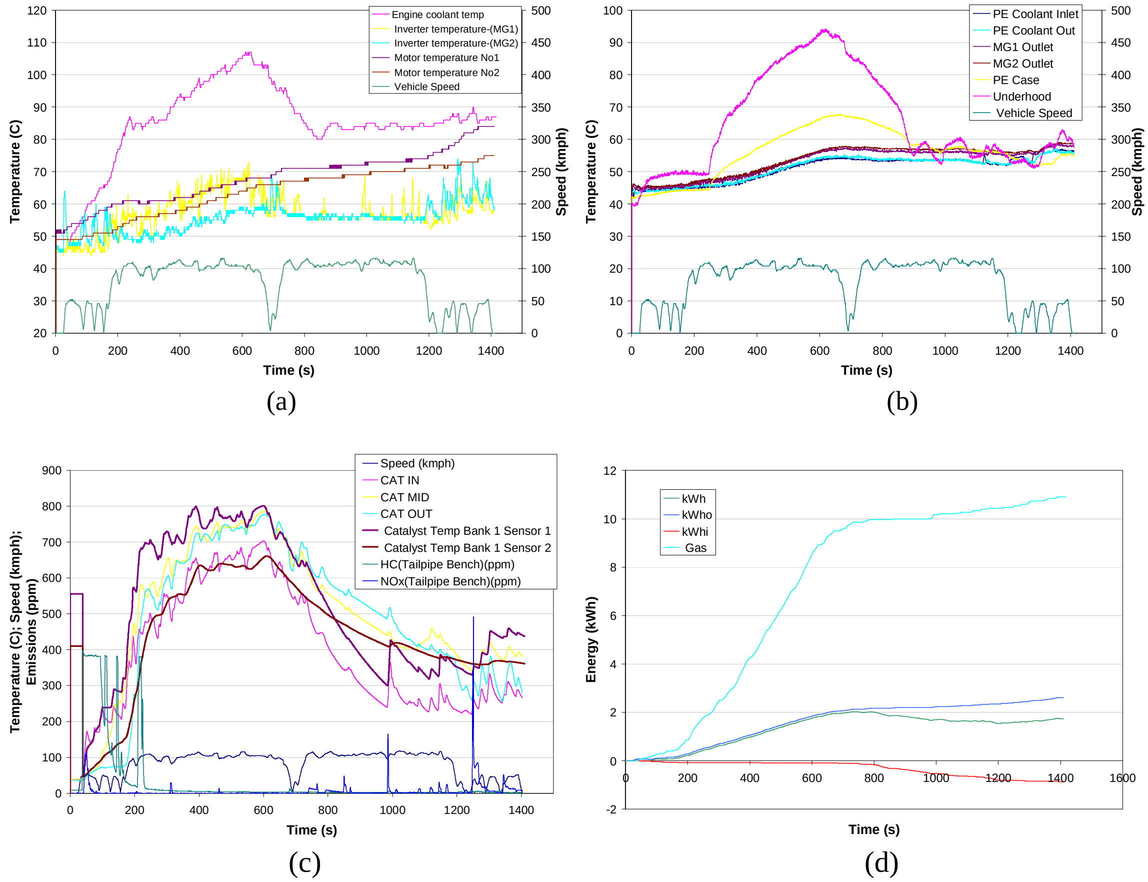


Figure 10: PHEV Dynamometer NREL to Genesee Roundtrip at 95ºF (35 ºC) Ambient

The same NREL to Genesee roundtrip cycle was performed with the PHEV on the dynamometer under controlled conditions. The dynamometer provides the added value of emissions measurement to correlate with vehicle events. Provided in Figure 10a-d are the results of the PHEV on this cycle at 95ºF (35ºC) ambient conditions. Inverter temperatures in both dynamometer and on-road cases have similar trends. Converter temperature was not available for this specific test. The Motor Temperature No.1 climbs steadily to almost 85ºC by the end of the trace as compared to ~60ºC for the on-road case (different ambient conditions). Figure 10c provides information on the catalyst operation. Of specific value is that the measured temperatures (CAT In, Cat Mid, and CAT Out) correlate well with the CAN bus catalyst temperature signals (Bank 1 Sensor 1 and Back 2 Sensor 2). Tailpipe emissions concentrations are shown for hydrocarbon (HC) and nitrous oxides (NOx). Hydrocarbon reduction is present above about 250ºC; however, under heavy load events bursts of emissions are still present even at 600ºC. NOx emissions occur during engine starts with catalyst temps below about 300ºC. Based on other emissions results, the cold start HC emissions are likely much higher than 400 ppm and the trend between 0 and 200s in Figure 10c is likely due to analyzer range limits. Comparing Figure 10d and 9d, while on the dyno the fuel consumption rate was slightly greater and there was some consumption even during the descent. The difference is likely due to driver and traffic variances. The electrical energy consumption characteristics are nearly the same.

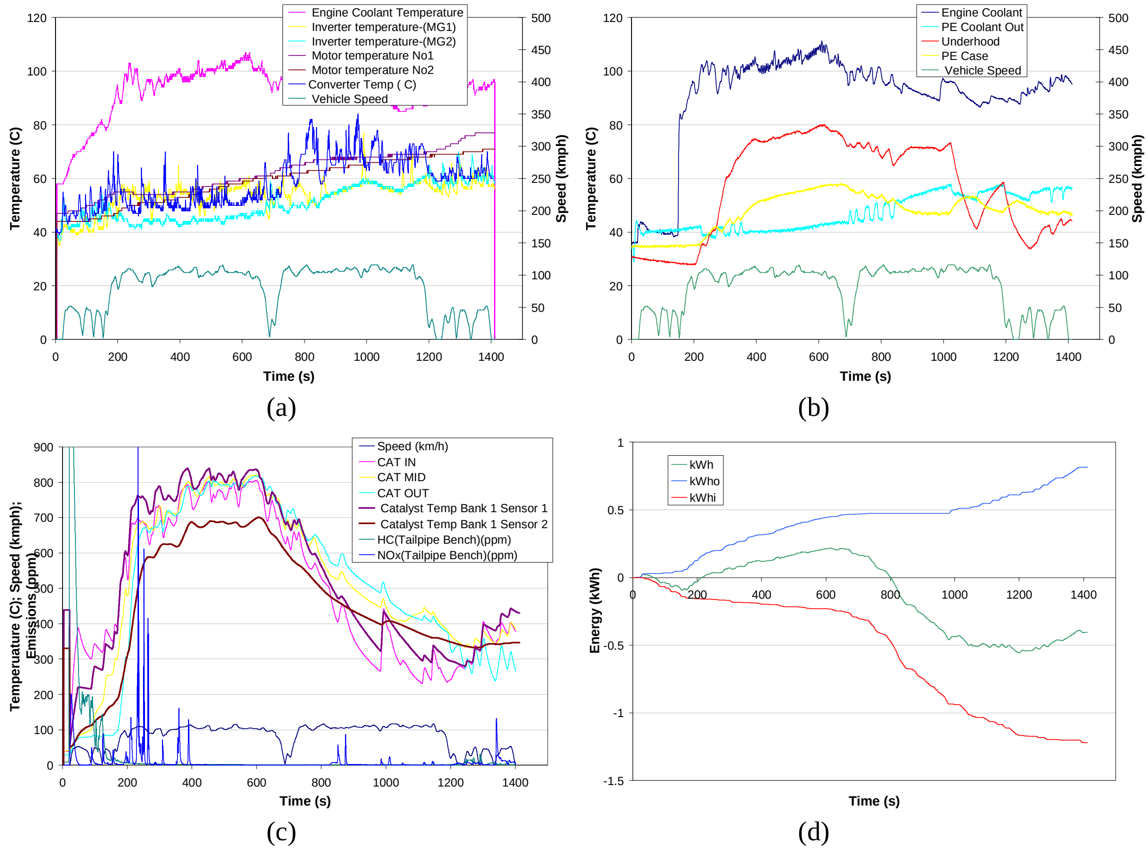


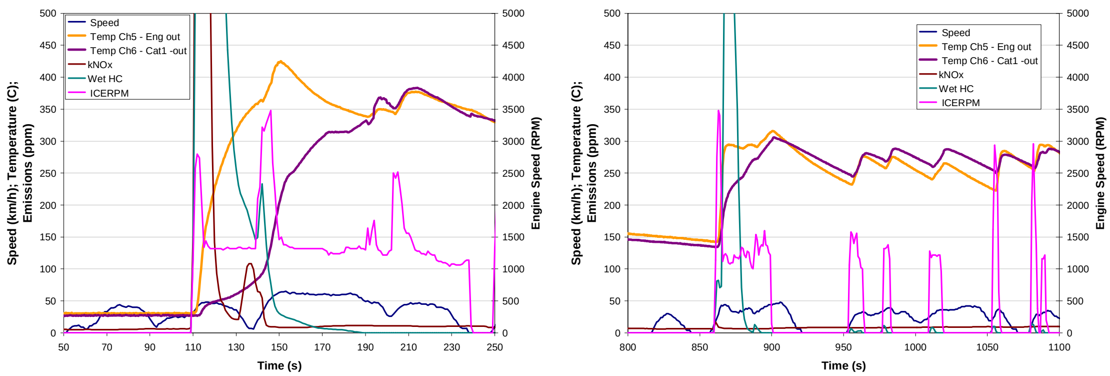
Figure 11: HEV Dynamometer Results for NREL to Genesee Roundtrip at 75ºF (24ºC) Ambient

Finally, Figure 11 provides similar results for the stock HEV prior to conversion tested at 75ºF (24ºC) ambient conditions. From the HEV to the PHEV some instrumentation was improved and therefore, identical channels are not available in each case. The power electronics CAN bus data does provide an interesting comparison to both PHEV data sets. The converter temp response is observed during the ascent portion is similar; however, the converter is clearly used aggressively during descent portion of the cycle. It was used very little for the PHEV during the descent. It is likely that both regenerative braking and the engine are being used to recharge the battery pack as this cycle is able to push the small NiMH battey pack to both the upper and lower extents of its usable window. Figure 11d shows that much less electrical energy is sourced from the pack. Continuous fuel consumption data was not calculated however the total cycle fuel consumption was 0.373 gallons (1.41 L) or 12.48 kWh and provides perspective on the relative use of gasoline vs. electrical energy between the PHEV and the HEV on challenging driving profile. From Figure 11c, a nearly identical catalyst thermal trend is observed to the PHEV. HC emissions seemed to be under control more quickly compared to the PHEV while a NOx event in the HEV occurs that seems to be correlated with the change in elevation between 200 and 400s. This difference suggests that both catalyst thermal and engine management with respect to driving events could be beneficial for PHEVs and HEVs.

4.3 PHEV On-road Emissions Measurement with a PEMs

The data presented in the previous section included both on-road operation and dynamometer operation. Dyno testing provides a controlled environment for collecting repeatable and accurate emissions trends. However, cycles on a dynamometer are not always representative of on-road operation and the correlation between measured emissions on the dynamometer and in-use emissions need further exploration.

New technology provides the ability to monitor emissions of an in-use vehicle with a portable device. A SEMTECH-DS portable emissions monitoring system (PEMs) was installed in the PHEV to assess the emissions trends while on the road. While reviewing the emissions data it is important to note that typical values measured with the PEMs for the Prius are near the detection and resolution limits of the system.



(a) (b)

Figure 12: Cold Start (a) and Hot Start (b) Comparison for PHEV On-road Using PEMs

In Figure 12, a close-up of two emissions scenarios are provided. In Figure 12a, the correlation between HC and NOx emissions with the vehicle speed, engine speed, and catalyst temperatures is observed for a cold-start driving event. Figure 12b, provides the same information for a hot-start event. In (a), the warm-up trend took ~60s under moderate load conditions. Both HC and NOx emissions are measurable during this period. For the warm start case, only the HC emissions are significant and the warm-up duration is ~30s. Following engine starts result in moderate emissions events likely due to the combination of relatively light engine loading and the catalyst thermal state.

The PEMs will be used more extensively as this project progresses to expand the understanding of the emissions potential of PHEVs and how control options may improve the emissions characteristics of PHEVs.

5. Future Research Steps

The results presented provide a sample of the data collected thus far and insights on HEV and PHEV operation including thermal systems challenges. Additional testing and laboratory experiments are planned to continue to expand the PHEV knowledge base. Specifically, an Exhaust Thermal Test Bench will provide a laboratory system for evaluating potential thermal management solutions to emissions issues of PHEVs. The test bench can be used with data from the vehicle to recreate engine thermal outputs and evaluate technologies like variable conductance catalyst technology or electrically heated catalysts prior to in-vehicle evaluations.

The EnergyCS PHEV system (single 9kWh battery pack) will be replaced with a Hymotion PHEV system (stock NiMH battery pack in parallel with a 5kWh Li-ion battery pack) for additional evaluation. Comparable data sets will be generated both on-road and on the dynamometer.

Finally, with NREL’s focus on renewable energy, the vehicle is planned to be used to evaluate recharge scenarios with renewable resources. Initially, this includes installation of an on-board solar array for trickle charging the PHEV pack when an outlet is not available. Giving this vehicle bi-direction energy flow capability is a goal that would then provide a tool for understanding the potential of using vehicles to provide grid support and aid with expansion of renewable generation technologies. This is an important step to use of renewable energy for transportation through the electric grid.

6. Conclusions

Systems analysis both by NREL and others continue to highlight the potential petroleum consumption benefits of PHEVs. The PHEV conversions of today's HEVs provide an early glimpse of real benefits while also identifying many of the challenges of the implementation. NREL's transportation research activities, supported by the U.S. DOE FreedomCAR Program, work to find component and systems solutions for future vehicle technology options. Vehicle testing of a 2006 Toyota Prius HEV converted to a PHEV by EnergyCS was conducted to compliment NREL's transportation research activities.

The testing has focused on evaluation of component and vehicle operation over real world conditions on the road with an emphasis on systems thermal management. Thermal management of the power electronics, energy storage, and emissions control systems will be critical for the success of both HEVs and PHEVs. The data collected includes both on-road and on dynamometer testing results.

Key accomplishments include:

- Vehicle instrumentation was completed and has been detailed in this paper that provides simultaneous collection of data from the vehicle CAN bus, the PHEV battery, and auxiliary sources including the power electronics and the exhaust system
- Testing of the vehicle in mountainous conditions was completed both on-road and on dynamometer under a range of ambient conditions both as a PHEV and an HEV
- Conditions were observed in both HEV and PHEV vehicle scenarios on a long mountain drive that limited their batteries ability to capture regenerative braking energy
- Thermal loading of the power electric components in HEVs and PHEVs are, in general, similar while thermal loading will be impacted by combination of the vehicle state and duty cycle
- On-road emissions analysis equipment was used to provide insights to catalyst thermal management for emissions reduction.

Although not an ideal implementation of a PHEV due to constraints of the Prius architecture, NREL's PHEV converted by EnergyCS provides a tool for evaluating the systems impacts of PHEV technology. Future work will include evaluation of the Hymotion PHEV system along with expansion of the research efforts to understand the ability of the PHEV storage system to interact with the utility grid providing grid support services that can aid in the expansion of renewable generation.

7. References

[1] Gonder, J., et. al. *Using GPS Travel Data to Assess Real-World Energy Use of Plug-In Hybrid Vehicles.* To be published in the Transportation Research Record (TRR), Journal of the Transportation Research Board (TRB), December 2007.

[2] Markel, T. and Simpson, A., *Cost-Benefit Analysis of Plug-in Hybrid Electric Vehicle Technology*. 2006. World Electric Vehicle Association Journal. WEVA-2006-053.

[3] *Plug-in Hybrid Electric Vehicle R&D Plan: FreedomCAR and Vehicle Technologies Program*. Working draft June 2007. http://www1.eere.energy.gov/vehiclesandfuels/pdfs/program/phev_rd_plan_june_2007.pdf. accessed Oct 2007.

[4] *FreedomCAR Battery Test Manual for Power-Assist Hybrid Electric Vehicles*. DOE/ID-11069. October 2003.

[5] Carlson, Richard W., et al. *Testng and Analysis of Three Plug-in Hybrid Electric Vehicles,* 2007. SAE Publication 2007-01-0283.

[6] *PHEVAmerica - Energy CS Plug-in Hybrid Test Report*. 2007. http://avt.inl.gov/pdf/phev/prius.pdf accessed Oct. 2007.

8. Acknowledgements

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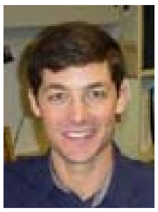
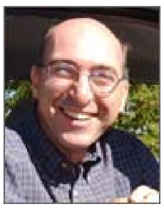
9. Authors

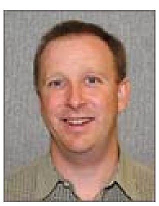


Tony Markel joined NREL in 1996. He received his master's degree in mechanical engineering from University of Colorado in 2005 and a B.S.E degree in mechanical engineering from Oakland University in 1995. He was instrumental in the development of the ADVISOR software tool for vehicle systems simulation and is skilled at using analysis and optimization tools to address real-world problems. He has supported simulations for setting requirements of batteries for advanced vehicles for the USABC. Mr. Markel is a member of the FreedomCAR Vehicle System Analysis Technical Team.



Ahmad Pesaran joined NREL in 1983 and has been working on various energy systems such as solar cooling, ocean thermal energy conversion, air conditioning, desiccant dehumidification/ cooling for buildings and buses, and since 1995, hybrid electric vehicle projects. He is currently the project manager for various activities related to energy storage such as battery thermal characterization, battery thermal analysis, electrical management and battery and ultracapacitor simulations for vehicle target analysis. Dr. Pesaran holds a Ph.D. in mechanical engineering from UCLA. He is a member of the FreedomCAR Electrochemical Energy Storage Technical Team and several of its workgroups.

Kenneth J. Kelly is currently the task leader for research and development of advanced thermal control technologies for advanced power electronics in NREL's Advanced Vehicles Group. Previously, he led NREL's efforts in Robust Design - for fuel cells and advanced heavy-duty hybrid electric vehicles. Ken also has experience with alternative fuel vehicle emissions testing with NREL's Alternative Fuels Utilization Program. He worked in industry as a manufacturing engineering with Swagelok Company. Ken holds M.S. and B.S. degrees in mechanical engineering from Ohio University.



Matthew Thornton is a Senior Engineer at NREL and the Vehicle Systems Analysis task leader. Prior to joining NREL in 2000, Matt earned a Ph.D from the Georgia Institute of Technology. Matt is involved in research programs that assess the fuel economy and performance impacts of advanced fuels, vehicle technologies, and powertrains for both light and heavy-duty vehicles.

Peter Nortman is President and Co-Founder of Energy CS. Mr. Nortman has over 20 years experience in development of vehicle systems, engineering design and battery traction system integration. He has been responsible for leading edge concept development, battery system design and failure mode analysis, safety and protection systems, cost optimization and manufacturability, and electric or hybrid electric vehicle traction system integration on over 40 system architectures. He has experience in a broad spectrum of electrochemical energy storage systems. At EnergyCS, Pete is the responsible manager for its programs on electric and hybrid electric vehicles ranging from the PHEV Prius, to conversion or custom built EVs, purpose built electric and hybrid buses and hybrid locomotives.

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